Renewable and Sustainable Energy Reviews 15 (2011) 1567–1574

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The effect of reactor design on the sustainability of grass biomethane

Anoop Singh[a,b], Abdul-Sattar Nizami[a,b], Nicholas E. Korres[a,b], Jerry D. Murphy[a,b,*]

[a] Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland
[b] Biofuels Research Group, Environmental Research Institute, University College Cork, Cork, Ireland

ARTICLE INFO

Article history:
Received 10 June 2010
Accepted 12 November 2010
Available online 12 January 2011

Keywords:
Anaerobic digestion
Grass
Biomethane
Biofuel
GHG emission

ABSTRACT

Grass biomethane is a sustainable transport biofuel. It can meet the 60% greenhouse gas saving requirements (as compared to the replaced fossil fuel) specified in the EU Renewable Energy Directive, if allowance is made for carbon sequestration, green electricity is used and the vehicle is optimized for gaseous biomethane. The issue in this paper is the effect of the digester type on the overall emissions savings. Examining three digestion configurations; dry continuous (DCAD), wet continuous (WCAD), and a two phase system (SLBR-UASB), it was found that the reactor type can result in a variation of 15% in emissions savings. The system that as modeled produced most biogas, and fuelled a vehicle most distance, the two phase system (SLBR-UASB), was the least sustainable due to biogas losses in the dry batch step. The system as modeled which produced the least biogas (DCAD) was the most sustainable as the parasitic demands on the system were least. Optimal reactor design for sustainability criteria should maximize biogas production, while minimizing biogas losses and parasitic demands.

Contents

* Corresponding author at: Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland. Tel.: +353 21 4902286; fax: +353 21 4276648.
E-mail addresses: apsinghenv@gmail.com (A. Singh), nizami_pk@yahoo.com (A.-S. Nizami), n.korres@ucc.ie (N.E. Korres), jerry.murphy@ucc.ie (J.D. Murphy).

1364-0321/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2010.11.038

Nomenclature

AD	anaerobic digestion
DCAD	dry continuous anaerobic digester
DS	dry solids
GHG	greenhouse gas
LCA	life cycle assessment
SLBR-UASB	sequential filled leach bed reactor complete with up-flow anaerobic sludge blanket
VS	volatile solids
WCAD	wet continuous anaerobic digester

1. Introduction

Substantial support programs for biofuels appeared across EU countries during the 1990s; this lead to significant growth in biofuel capacity [1]. The concept of these biofuels was to alleviate concerns regarding climate change and oil dependence [2,3]. The EU Biofuels Directive set targets for biofuels [4] but subsequent concerns lead to the EU Renewable Directive which set sustainability criteria including minimum GHG emissions savings [5]. It was shown by Murphy and Power [6] that in comparison to energy crops, the utilization of grassland in Ireland for the production of clean indigenous biofuel has numerous advantages. The reduction in the national herd, the extent of grass land (91% of agricultural land) and Cross Compliance leads to an excess of grassland which may not be converted to arable land and energy crop production. Thus grass biomethane does not affect domestic food supplies and has minimum land use change issues [6]. The optimization and sustainability of grass biomethane depends on the net energy production and reduction in greenhouse gas (GHG) emissions [7]. Korres et al. [8] reported 21.5% GHG emissions savings as compared to the fossil fuel displaced (diesel) for a grass biomethane system using a Continuously Stirred Tank Reactor (CSTR). This can be increased (to 75%) by using green electricity to satisfy the parasitic demand, using an efficient vehicle, and allowing for a conservative level of carbon sequestration in the grassland. This exceeds the sustainability limit of 60% GHG savings for biofuel facilities built after 2017 (60%) [5].

Nizami and Murphy [9] described the digester configurations applicable for grass digestion. These are distinguished and characterized based on: dry or wet process; batch or continuous process; number of phases or stages of digestion activities; operating temperature (thermophilic or mesophilic); retention time and organic loading rate. Efficiency may be said to be defined by increased methane yields at reduced hydraulic retention time [10]. GHG emissions savings may vary depending on type of digester used. Availability of commercial data on mono-digestion of grass silage is limited [11]. In most of the digester systems, the grass is used as co-substrate with manure and maize silage [12]. This paper will examine three reactor configurations: dry continuous anaerobic digester (DCAD); wet continuous anaerobic digester (WCAD); and sequential leach bed reactors coupled with an upflow anaerobic sludge blanket (SLBR-UASB) (Fig. 1). The analysis will focus on the energy balance and GHG emissions savings as compared to replaced diesel.

2. Methodology

2.1. Life cycle assessment (LCA)

LCA allows the identification of opportunities for improvement [13,14]. This paper purports to undertake a LCA analysis from field to wheel of grass biomethane in a similar manner to Korres et al. [8]. In this analysis particular attention is paid to relative merits of the digester configuration. Comparisons between environmental consequences of choosing one system or digester over the other, as in this study, lead to consequential LCA [15]. The consequential approach requires that the LCA is comparative, that alternatives are equivalent hence comparable not just regarding the primary service, which is the "main function" of the system (transport fuel in this instance), but also on all secondary services such as the nutrient value of the digestate which replaces mineral fertilizers. Estimation of GHG emissions savings is based on the methodology proposed in the EU Renewable Directive 2009/28/EC [5]. The functional unit is defined as m^3 biomethane per annum and the Global Warming Potential (GWP) is expressed as g CO_2 equivalent (CO_2e) km^{-1} vehicle travel.

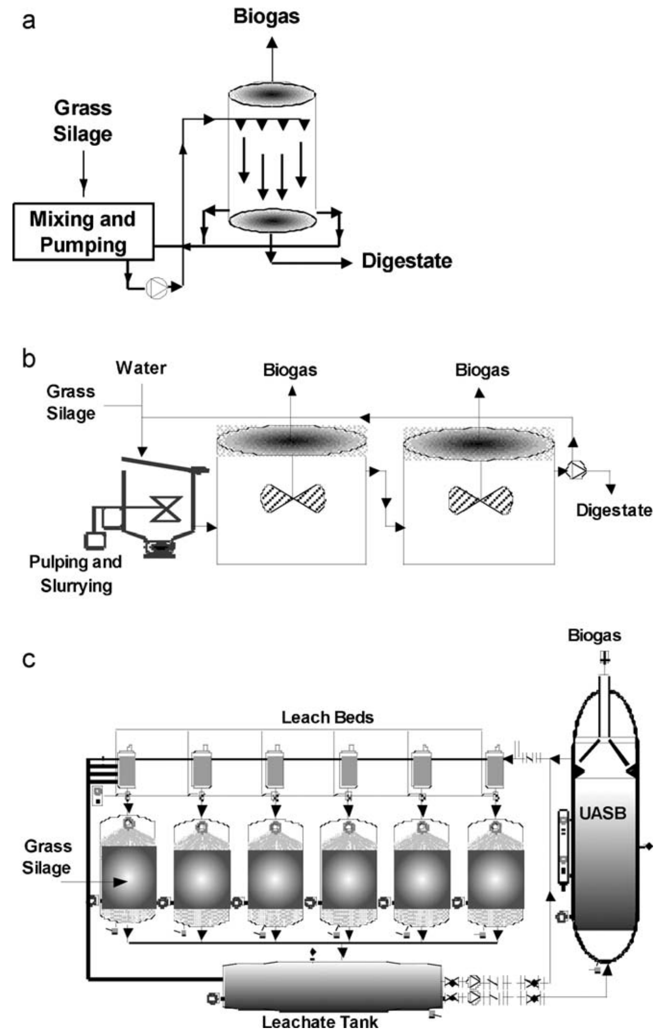


Fig. 1. Different anaerobic digesters ((a) DCAD; (b) WCAD; (c) SLBR-UASB) for biomethane production from grass silage.

2.2. Production of grass silage

The husbandry of the grassland is as described by Korres et al. [8] and tabulated in Table 1. Fertilizer is applied at the rate of 75, 70 and 100 kg ha^{-1} (N, P and K) respectively at the establishment year, 125, 20 and 200 kg ha^{-1} after first harvest and 100, 10 and 95 kg ha^{-1} after second harvest [16]. Digestate, a co-product from biomethane production, is used as a substitute fertilizer and provides 102 kg N, 4.2 kg P and 149.7 kg K ha^{-1} a^{-1} [8]. Supplementary mineral fertilizers to cover the nutritive needs of the crop (for the production of 12 t DM ha^{-1} a^{-1}) after the applica-

Table 1
Husbandry details for grassland establishment and maintenance.

Farm area	137.5 ha
Grass species	*Lolium perenne* (rye grass)
Reseeding frequency	8 years
Seeding rate	25 kg ha^{-1}
Lime	10 t ha^{-1} per 8 years
Herbicide	Glyphosate (Pre-emergent), Asulam (post-emergent)
Harvesting frequency	Two per year (May and July)

tion of digestate are reduced to 123 kg N, 25.8 kg P and 145.3 kg K ha^{-1} a^{-1}.

2.3. Production of biomethane

Anaerobic digestion is a ubiquitous technique for converting organic, wet biomass into renewable energy in the form of biogas which may be upgraded to biomethane and subsequently used as a transport fuel in a compressed natural gas (CNG) vehicle [17,18]. In this study three differently digester systems are selected for grass biomethane production. The farm size (137.5 ha, Table 1) and transportation distance (10 km) as modeled is the same as Korres et al. [8] and Smyth et al. [18]. Diesel is assumed to be the displaced transport fuel.

3. Reactor configurations

3.1. Dry continuous anaerobic digester (DCAD)

The dry continuous anaerobic digestion system is used in a number of European countries including Germany, Belgium, Switzerland and Austria. This system typically operates under thermophilic conditions (50–58 °C) [19] and is classified as a single stage system. In this study the operating temperature is considered as 50 °C as in the case of De Baere [20–22]; in the Brecht, Nüstedt, Kaiserslautern and several other DCAD systems. The volatile solids (VS) content within the system varies from 15 to 40% of wet biomass [19]. This is similar to pit silage (∼200 kg VS t^{-1}) as may be noted in Table 2. The grass silage is macerated for optimum operation to less than 4 cm before feeding to the digester. The mixing ratio of substrate and digestate is taken as 1:7. Data from De Baere would suggest biogas production of 90–120 m^3 t^{-1} grass silage at a retention time between 20 and 30 days [21]. In this study maximum biogas production is taken as 105 m^3 t^{-1} grass silage (≈292 m^3 CH_4 t^{-1} VS) at 30 days retention time.

3.2. Wet continuous anaerobic digester (WCAD)

The WCAD system, with two digesters operating in series (at less than 10% DS) at 38 °C, considered in this study is based on Korres et al. [8] and Smyth et al. [18]. The temperature of the incoming substrate is 10 °C, which is typical for the south of Ireland. The loading rate is taken as 1.44 kg volatile solids (VS) m^{-3} day^{-1}. Approximately 45.2 m^3 substrate (@ 10% DS) is fed into the first digester every day. The total retention time is 62.5 days and the substrate remains about half of the time in each digester. The substrate flows by gravity from the first to the second digester and the liquid is circulated back to the first digester. Maceration and mixing may allow optimal digestion of the feedstock by keeping the material homogenous and in suspension. The produced grass silage (7500 t a^{-1}) is mixed initially with 9000 t of water to obtain the desired DS level (i.e. 10%). A yield of 550 m_n^3 biogas per tonne VS (302 m_n^3 CH_4 t^{-1} VS) added to the AD plant is assumed on the basis of 55% destruction of VS [8,18].

3.3. Sequential leach bed reactor complete with upflow anaerobic sludge blanket (SLBR-UASB)

The SLBR-UASB system is the combination of two systems, the batch reactor and the upflow anaerobic sludge bed (UASB) reactor [9]. In batch digesters, the reactor vessel is loaded once with raw feedstock for a certain period of time, until complete degradation has occurred [23]. The reactor is then half emptied leaving the other half as an innoculum for the next batch. The UASB contains the dense pellets of anaerobic bacteria that allows high organic loading rate in a liquid stream [24]. Coupling the leach beds with a UASB allows double the capacity in the leach beds as the batch chambers may be completely emptied on each cycle. The leach beds are now used for the hydrolysis stage while the UASB is used for the methanogenic stage. The SLBR-UASB in this study consists of six leach beds (488 m^3 each), one leachate tank (423 m^3) and one UASB (636 m^3) as described in Box 1 ; a mesophillic temperature regime (38 °C) is proposed. The grass silage is loaded sequentially in the leach bed with a regular interval of 6 days, resulting in a retention time of 36 days. The loading rate is modeled as 50 kg VS m^{-3} day^{-1}. A solid liquid ratio of 1:8 is used, similar to a study conducted by Lehtomäki et al. [25]. A VS destruction of 55% results in 7.5 kg Chemical Oxygen Demand (COD) m^{-3} leachate (1.42 kg COD is generated per 1 kg VS destruction) [11]. Hulshoff Pol et al. [26] reported that high volumetric loading rates of over 50 kg COD m^{-3} day^{-1} could be well accommodated under mesophillic conditions in a UASB. Nizami and Murphy [9] suggest more feasible rates of 20 kg COD m^{-3} day^{-1}. In this study the organic loading rate of 10 kg COD m^{-3} day^{-1} is considered to provide longer time for

Table 2
Biomethane yield of different anaerobic digestion systems.

	DCAD	WCAD	SLBR-UASB
Farm size (ha)	137.5	137.5	137.5
Silage yield (t a^{-1}) @ 22%DS	7500	7500	7500
DS (t a^{-1})	1650	1650	1650
VDS (t a^{-1}) @ 90% of DS	1485	1485	1485
Volume of digester required (m^3)	1055.5	2825.3	2929.3
Loading rate (kg VS m^{-3} day^{-1})	3.85	1.44	1.39
Retention time (days)	30	62.5	36
Biogas production (m_n^3 ha^{-1} a^{-1})	5727	5940	6415
Biomethane production (m_n^3 ha^{-1} a^{-1})	3150	3368	3637
Losses in digestion (m_n^3 ha^{-1} a^{-1})	0	0	36
Losses in upgradation and compression (m_n^3 ha^{-1} a^{-1})	63	67	73
Net biomethane production (m_n^3 ha^{-1} a^{-1})	3087	3300	3565
Energy in net biomethane produced (GJ ha^{-1} a^{-1})	113	121	131
Energy replaced by biomethane (GJ ha^{-1} a^{-1})	93	99	107
Distance travelled by 1600 cc car (km ha^{-1} a^{-1})	48,691	51,832	56,021

Box 1: Description of SLBR-UASB.

Quantity of grass silage (feed stock)	=7500 t a^{-1}
DS @22%	=1650 t a^{-1}
VS @90% of DS	=1485 t a^{-1}
VS available for AD	=4.07 t day^{-1}
Loading rate	=50 kg VS m^{-3}
Number of leachbeds	=6
Retention time	=36 days
Volume of each leach bed	=4.07*1000*6/50
	=488.22 m^3
Quantity of feedstock in leachbeds	=(7500/365)*6 = 123.29 t/leachbed
Quantity of water required for maintaining liquid solid ratio (1:8)	=(123.29*0.22*8) – (123.29*0.78)
	=120.82 t or m^3
Volume of leachate tank	=120.82*(1/6 + 2/6 + 3/6 + 4/6 + 5/6 + 6/6)
	=422.88 m^3
Quantity of feedstock in all leachbeds	=123.29*6 = 739.73 t
Quantity of VS	=739.73*0.22*0.9 = 146.47 t
1 kg VS	=1.4 kg COD
COD generated @ 55% VS destruction	=146.47*0.55*1.42 = 114.39 t/36 days
	=114.39/36 = 3.18 t day^{-1}
Influent COD	=3.18*1000/422.88 = 7.51 kg m^{-3}
Organic loading rate (OLR)	=10 kg COD m^{-3} day^{-1}
Working volume of UASB	=Influent flow rate*Influent COD/OLR
	=422.88*7.51/10 = 317.75 m^3
Actual volume of UASB	=317.75*2
	=635.5 m^3

(Equal volume is required for liquid destruction at the bottom and three phase separator at top)

methanogenesis. The methane production in systems similar to the SLBR-UASB using grass silage as substrate is reported in the range of 0.27–0.39 m^3 CH_4 kg^{-1} VS added [9,27,28]. In the present study an average methane yield of 330 m^3 CH_4 t^{-1} VS added is considered.

3.4. Biomethane production and use

The maximum biogas production potential from grass silage was estimated as 6415 $m_n{}^3$ ha^{-1} a^{-1} in SLBR-UASB system (Table 2). The methane loss during upgradation and compression process is assumed to be 2%, giving a net biomethane production of 3087, 3300 and 3565 $m_n{}^3$ ha^{-1} a^{-1} or 113, 121 and 131 GJ energy ha^{-1} for DCAD, WCAD and SLBR-UASB system respectively.

Korres et al. [8] stated that it is a necessity to scrub and to compress the biomethane to 300 bar for onsite storage and discharge to the vehicle through cascading pressure reduction to 250 bar. This may be done on site or alternatively the existing natural gas infrastructure may be used as a distribution system. According to a EC report [29], the energy required for local distribution of natural gas is zero, because the high pressure trunk lines (typically operating at between 35 and 70 bar) that feed low pressure networks (typically operating at 7 bar) provide sufficient energy to supply local demand.

Bi-fuel vehicles are able to run on either liquid fossil fuel (petrol or diesel) or compressed gas (either natural gas or biomethane). The bi-fuel car is tuned and optimized for the liquid fossil fuel and thus is not optimized for the gaseous fuel due to the lower flame speed of the air–gas mixture compared to air–petrol mixture [8]. Power and Murphy [30] reported that existing bi-fuel vehicular engines are 18% less efficient (km MJ^{-1}) operating on gaseous than liquid fuel. This is also supported by an Australian public discussion paper [31] in which it states that biogas is 18% and 29% less efficient than diesel and petrol fuels respectively. A bi-fuel car of 1600 cc is assumed for the present study, with an 18% reduction in engine efficiency when compared to diesel. Sustainable Energy Ireland (SEI) [32] reported that 5.3 L diesel is required for a 1600 cc car to travel 100 km, which is equivalent to 1.91 MJ km^{-1} travel. An 18% less efficient car will require 2.33 MJ km^{-1} travel. Thus the biomethane produced by DCAD, WCAD and SLBR-UASB system can replace diesel equivalent of about 93, 99 and 107 GJ ha^{-1} respectively (Table 2).

4. Energy consumption and related emissions

4.1. Grass-silage production

Korres et al. [8] studied energy consumption and related emissions for the production of grass silage at Irish farms and reported that 15.7 GJ ha^{-1} a^{-1} energy consumption is required in various agricultural operations (i.e. energy consumed during crop husbandry and that for the production and transportation of chemicals/fertilizers and lime) (Table 3). The total GHG emissions (i.e. fuel consumption, herbicide volatilization, N_2O emission, lime dissolution, and those of agrochemicals and seed production) were equivalent to 2028 kg CO_2e ha^{-1} a^{-1}. Thus the GHG emissions during the grass silage production by the DCAD, WCAD and SLBR-UASB systems is equivalent to 41.8, 39.1 and 36.2 g CO_2e km^{-1} (Table 3).

4.2. Transportation of grass and grass-silage

Transportation of harvested plant material from farm to silage pit and from there to AD plant is made by trucks at an expense of 0.7 MJ energy tkm^{-1} excluding empty return [33]. The transportation of 7500 t grass per annum from field to silage pit (10 km) requires 52.5 GJ. Transportation of grass silage to the AD plant (5 km) requires 37.5 GJ energy (Table 4). The total energy required during these operations is 90 GJ a^{-1}, equal to 2500 L diesel. Total emissions are estimated at about 8 t CO_2e a^{-1} (88.8 g CO_2e MJ^{-1} diesel). Under the systems examined in this paper this equates to 1.2, 1.1 and 1.0 g CO_2e km^{-1} vehicle travel by DCAD, WCAD and SLBR-UASB systems respectively (Table 4).

Table 3
Energy consumption and GHG emissions during grass cultivation.

Activity	Energy consumed ($GJ\ ha^{-1}\ a^{-1}$)	GHG emissions (kg $CO_2e\ ha^{-1}\ a^{-1}$)	GHG emissions (g $CO_2e\ km^{-1}$ vehicle travel)		
			DCAD	WCAD	SLBR-UASB
Direct energy consumption for various agronomic operations	2.98	264.5	5.4	5.1	4.7
Indirect energy consumption for various material required for grass production	12.63	628.5	13.0	12.1	11.2
Herbicide volatilization	–	5.4	0.1	0.1	0.1
N_2O emission	–	525.0	10.8	10.1	9.4
Lime dissolution	–	550.0	11.3	10.6	9.8
Lime transportation	0.10	55.0	1.1	1.1	1.0
Total	15.71	2028.4	41.8	39.1	36.2

Table 4
GHG emissions in transportation of grass and grass silage.

	Energy required ($GJ\,a^{-1}$)	GHG emissions (kg $CO_2e\,a^{-1}$)	GHG emissions (kg $CO_2e\,ha^{-1}\,a^{-1}$)	GHG emissions (g $CO_2e\,km^{-1}$ vehicle travel)		
				DCAD	WCAD	SLBR-UASB
Grass	52.5	4664	33.9	0.7	0.6	0.6
Grass silage	37.5	3331	24.2	0.5	0.4	0.4
Total	90	7995	58.1	1.2	1.1	1.0

4.3. Preparation and feeding of grass-silage in digester

Maceration of the grass silage, before feeding the digester, is a pre-process operation for particle size reduction to prevent any possible physical obstruction of pipes and pumps by the fibres while at the same time increasing the surface area available for microbial attack [8,11]. The electrical energy demand for maceration equals to $2\,kW_eh\,t^{-1}$ [18]; this is assumed to be supplied by the electric grid. At present 542.8 kg $CO_2e\,MW_eh^{-1}$ is produced in the Irish grid [34]. The maceration of 7500 t grass silage requires $15\,MWh\,a^{-1}$ electricity, equivalent to 8142 kg $CO_2e\,a^{-1}$ (Table 5). The pumping of grass silage and water to the digester is taken as $0.2\,kWh\,m^{-3}$ (assuming 4 kW pump with capacity of $20\,m^3\,h^{-1}$) [35]. Pumping of grass silage in DCAD system requires $12\,MWh\,a^{-1}$ electricity whereas water pumping in WCAD and SLBR-UASB system requires 1.8 and 30.9 $MWh\,a^{-1}$ electricity respectively. The emissions due to electricity for pumping of grass silage and water are as outlined in Table 5. Total emissions for preparation and feeding of grass silage are 2.2, 1.3 and 3. 3 g $CO_2e\,km^{-1}$ vehicle travel for DCAD, WCAD and SLBR-UASB systems respectively (Table 5).

4.4. Anaerobic digestion of grass-silage

The supply of thermal energy for the digester is modeled as natural gas with an emission factor of 240 g $CO_2\,kWh^{-1}$. In the DCAD system, the temperature of the digester is maintained by injecting steam in the mixing part of the digester. Heat losses in the digester are minimal because of high solid concentration that greatly reduces convection losses; insulation can maintain the temperature in the digester in a steady state [20,22]. The amount of heat provided by metabolic generation is uncertain and therefore neglected, giving more conservative results. The thermal energy for the DCAD system is 5.8% of the produced biogas [36] and equates to $949\,GJ\,a^{-1}$ with corresponding emissions of 63.8 t $CO_2e\,a^{-1}$ or 9.6 g $CO_2e\,km^{-1}$ vehicle travel (Table 6). Biogas losses during production are considered negligible in DCAD and WCAD systems.

WCAD requires continuous mixing to keep the material homogenous within the digester [8]. The electrical demand for mixing a slurry digester (operating at about 12% DS) equals $10\,kWh\,t^{-1}$ [35]. It is assumed that the same amount of energy is required for mixing grass silage in a WCAD system (at 10% DS). This equates to $165\,MW_eh\,a^{-1}$ (or $589\,GJ\,a^{-1}$ of final energy) corresponding to emissions of 89.6 t $CO_2e\,a^{-1}$ or 12.55 g $CO_2e\,km^{-1}$ vehicle travel (Table 6).

The heat loss from the WCAD and SLBR-UASB systems is calculated using Eq. (1). The energy required to heat the feed stock is calculated by Eq. (2) [37]:

$$hl = UA\,\Delta T \tag{1}$$

$$q = CQ\,\Delta T \tag{2}$$

where hl is the heat loss ($J\,s^{-1}$); U is the overall coefficient of heat transfer ($W\,m^{-2}\,^{\circ}C$); A is the cross sectional area through which heat loss is occurring (m^2); ΔT is the temperature drop across the surface (°C); q is the heat required to raise feedstock to digester temperature ($kJ\,s^{-1}$); C is the specific heat of the feedstock ($kJ\,kg^{-1}\,^{\circ}C^{-1}$); Q is the volume to be added (kg).

The coefficient of heat transfer for the wall, floor and roof of the digester is taken as 0.8, 1.7 and 1 $W\,m^{-2}\,^{\circ}C$ respectively [38]. The temperature drop across the surface and the temperature difference between the feed stock and digester temperature is assumed to be 28 °C. The volume of feedstock added daily in the WCAD system is 45.21 m^3 at 10% DS. As the feedstock has a low solids content its specific heat is assumed to be similar to that of water ($4.2\,MJ\,t^{-1}\,^{\circ}C$) [8,18,38]. The emissions associated with heating the digester in the WCAD system is 222 t $CO_2e\,a^{-1}$ or 31.1 g $CO_2e\,km^{-1}$ vehicle travel. Consequently, the total emissions in the WCAD system (mixing and temperature maintenance) are 43.6 g $CO_2e\,km^{-1}$ vehicle travel emission (Table 6).

The emissions associated with heating (including heat loss) the SLBR-UASB system is $3286\,GJ\,a^{-1}$ which is equivalent to 221 t $CO_2e\,a^{-1}$ or 28.6 g $CO_2e\,km^{-1}$ emissions of vehicle travel. Lehtomäki et al. [25] reported that the 98% of total methane originated from the UASB and the rest (2%) from the leach beds. Feeding and removing grass silage and digestate from the leach bed after the completion of each operational cycle i.e. every 30 days, results in biogas losses from the system which is assumed equal to 1%. This provides a further addition 11.5 g $CO_2e\,km^{-1}$ vehicle travel in the system (Table 6).

4.5. Upgrading and compression of biomethane

The electrical demand for biogas scrubbing and compression is in the range 0.3–0.6 and 0.35–0.63 $kWh\,m^{-3}$ upgraded biomethane, respectively [6,29,39]. A value of 0.35 $kWh\,m^{-3}$ is assumed for each operation, which equates to an annual electrical demand of 297, 318 and 343 MW_eh for the DCAD, WCAD and SLBR-UASB systems respectively. This equates to 161, 172 and 186 t CO_2e respectively or 24.1 g $CO_2e\,km^{-1}$ vehicle travel for each system (Table 7). Methane losses during the upgrading and compression of biogas are taken

Table 5
GHG emissions in preparation and feeding of grass silage in different anaerobic digestion systems.

Activity	Energy required ($MW_eh\,a^{-1}$)			GHG emission (kg $CO_2e\,a^{-1}$)			GHG emission (g $CO_2e\,km^{-1}$ vehicle travel)		
	DCAD	WCAD	SLBR-UASB	DCAD	WCAD	SLBR-UASB	DCAD	WCAD	SLBR-UASB
Maceration	15	15	15	8142	8142	8142	1.2	1.2	1.1
Pumping (grass silage/water)	12	1.8	30.9	6514	977	16756	1.0	0.1	2.2
Total	27	16.8	45.9	14656	9119	24898	2.2	1.3	3.3

Table 6
GHG emissions from different anaerobic digestion systems.

	Energy required ($GJ\,a^{-1}$)	GHG emission ($kg\,CO_2e\,a^{-1}$)	GHG emission ($g\,CO_2e\,km^{-1}$ vehicle travel)
DCAD			
Heating digester	949	63778	9.6
Total	949	63778	9.6
WCAD			
Mixing	589	89562	12.6
Heat loss from digester 1	681	45785	6.4
Heat loss from digester 2	681	45785	6.4
Heating digester 1	1940	130395	18.3
Total	3892	311527	43.6
SLBR-UASB			
Heat loss from leachbeds	1735	116587	15.1
Heat loss from leachate tank	263	17656	2.3
Heat loss from UASB	356	23933	3.1
Heating of the feed stock in leachbeds	882	59270	7.7
Heating of the water in leachate tank	50	3342	0.4
Escape of biogas	–	88334	11.5
Total	3286	309123	40.1

Table 7
GHG emissions in upgradation and compression of biomethane produced in different anaerobic digestion systems.

	DCAD	WCAD	SLBR-UASB
Energy required for upgrading and compression ($kWh\,a^{-1}$)	297124	317691	343106
GHG emission in upgradating and compression $kg\,CO_2e\,a^{-1}$	161279	172442	186238
$g\,CO_2e\,km^{-1}$ vehicle travel	24.1	24.1	24.1
Escape of biomethane during upgradation and compression process ($m^3\,a^{-1}$)	8663	9262	10003
GHG emissions due to escape of biomethane $kg\,CO_2e\,a^{-1}$	137988	147539	159343
$g\,CO_2e\,km^{-1}$ vehicle travel	20.7	20.7	20.7
Total GHG emissions in upgradation and compression $kg\,CO_2e\,a^{-1}$	299278	319993	345591
$g\,CO_2e\,km^{-1}$ vehicle travel	44.8	44.8	44.8

as 2% of biomethane [40]. According to Murphy and McKeogh [41] each m^3 of biogas which escapes and is not combusted, produces 9.16 kg of CO_2e. Thus estimated emissions are 138, 148 and 159 t $CO_2e\,a^{-1}$ for the DCAD, WCAD and SLBR-UASB systems respectively. This is equivalent to 20.7 g $CO_2e\,km^{-1}$ vehicle travel. The total emission in upgrading and compression of biomethane is 44.8 g $CO_2e\,km^{-1}$ vehicle travel (Table 7).

5. Sensitivity analysis

5.1. Base case

The summary of GHG emissions of grass biomethane production by different anaerobic digesters is presented in Fig. 2. Silage production, upgrading and compression of biomethane, and parasitic energy demand in the anaerobic digestion process are the main contributors to GHG emissions. The total emissions for the average 1.6 L diesel car using 5.3 L of diesel per 100 km is 169.6 g $CO_2e\,km^{-1}$ vehicle travel. The GHG emissions savings over diesel of grass biomethane (produced in different AD systems) is given in Table 8. Following the methodology of Korres et al. [8] the following scenarios which improve GHG emissions savings may be assessed.

5.2. Wind energy

The GHG emissions originating from the consumption of electricity can be reduced through use of renewable energy (e.g. wind energy). The highest possible energy value from wind energy (i.e. 46.4 g $CO_2e\,kWh_e^{-1}$) as reported by Korres et al. [8] is considered for analysis. A reduction of 14–20% in GHG emissions was estimated when the energy from Irish electric grid was replaced by electricity from wind energy in each digester design studied in this paper. The GHG savings over diesel ranges from 41 to 56%. This secures the classification of grass biomethane as a sustainable biofuel for the year up to 2017 (Fig. 3 and Table 8).

Table 8
GHG emissions comparison of a 1.6 L diesel vehicle operating on diesel compared to grass biomethane.

Scenario		$g\,CO_2e\,km^{-1}$ vehicle travel	% reduction
Conventional	Diesel	169.6	
Base case	DCAD	99.5	41.3
	WCAD	129.9	23.4
	SLBR-UASB	125.3	26.1
Wind energy	DCAD	75.5	55.5
	WCAD	95.2	43.9
	SLBR-UASB	100.3	40.9
Vehicle efficiency	DCAD	61.8	63.5
	WCAD	78.1	54.0
	SLBR-UASB	82.3	51.5
Carbon sequestration	DCAD	24.7	85.4
	WCAD	43.3	74.4
	SLBR-UASB	50.1	70.5

Combining scenarios from top to bottom, i.e. carbon sequestration includes for the benefits of wind energy and vehicle efficiency.

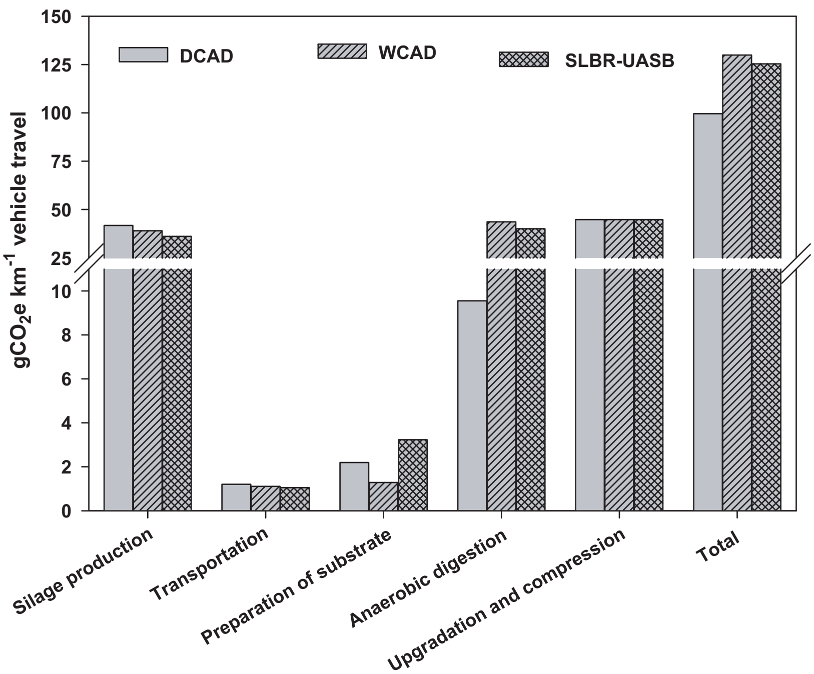


Fig. 2. GHG emission in the production of biomethane from different anaerobic digestion systems for 1 km vehicle travel.

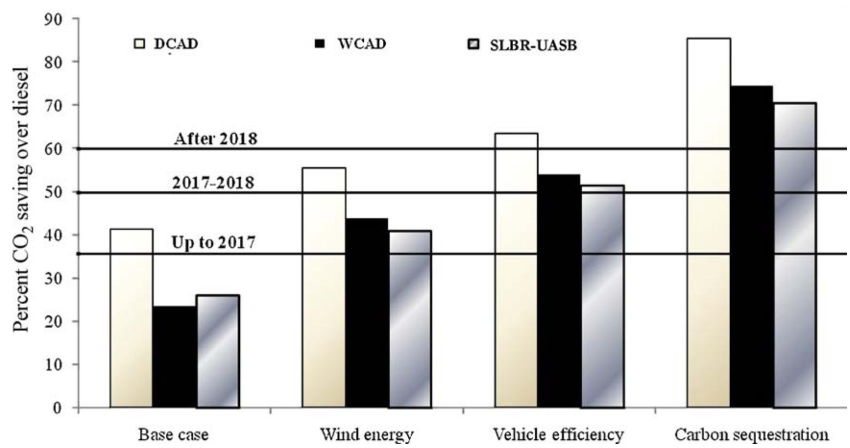


Fig. 3. Percent CO_2 savings over fossil diesel under various scenarios of biomethane production in different anaerobic digesters. The horizontal lines represent the limits of GHG savings for biofuels. (The scenarios are combined from left to right; carbon sequestration includes for the benefits of wind energy and vehicle efficiency.)

5.3. Vehicle efficiency

Natural gas is less efficient than diesel in the existing fleet of bi-fuel cars under combined load conditions, primarily due to throttling losses [42]. Improvements in engine efficiency to a similar km MJ^{-1} as diesel is imminent with the increasing production of CNG cars. This will lead to improved emissions saving (Fig. 3). The combined GHG savings over diesel ranges from 52 to 64% (Table 8 and Fig. 3).

5.4. Carbon sequestration

Carbon sequestration in arable and perennial grass crops varies greatly between 1.2 and 4.4 t ha^{-1} of C [43–45]. According to Kiely et al. [43] Irish grasslands act as carbon sink within a range, across different counties of South and South East Ireland, between 0.3 and 0.75 t of C ha^{-1} a^{-1}. Freibauer et al. [46] and Jones and Donnelly [47] reported that the minimum potential of soil carbon sequestration rate for perennial ryegrass and permanent crops under European agricultural conditions is 0.6 t C ha^{-1} a^{-1}. Adopting this value in the present study all anaerobic digestion systems provide more than 60% GHG saving over diesel (Table 8 and Fig. 3), which secures the sustainability of biomethane as a biofuel after 2018.

6. Conclusions

Grass biomethane is sustainable as defined by the EU Renewable Energy Directive [5]. Allowing for green electricity, an efficient vehicle and carbon sequestration the 60% GHG savings over the replaced fossil fuel required for new facilities built after 2017 can be readily achieved. This was previously shown by Korres at al. [7] with the limitation that emissions from digestate spreading are not allowed for due to difficulties in assessing these emissions. The effect of the reactor design is interesting, generating a range of 15% in savings. The systems as modeled must be seen as models due to the very few digesters mono-digesting grass.

Dry continuous digestion (DCAD) as modeled generated the least quantity of gas, the least km travelled by the vehicle (Table 2).

However the low thermal parasitic demand of this system in comparison to the other two systems modeled leads to the lowest production (g CO_2/km) of the three modeled systems.

The wet system (WCAD) produced neither the maximum or minimum quantity of biomethane but as modeled has the largest parasitic electrical demand. In the base case this leads to it being the least sustainable process but allowing for green electricity it becomes the middle ranking system.

The two phase system (SLBR-UASB) as modeled produces most biogas and provides most kilometers travelled. It weakness is the loss of biogas in the batch digesters. This leads to it being the least sustainable system.

The comparison of the systems would highlight the following attributes for a sustainable anaerobic digester system:

- Maximize the production of biogas from the system
- Minimize the losses of biogas from the system
- Minimize parasitic demands of the system
- Use green electricity

Funding

Environmental Protection Agency (EPA) Strive Programme: "Compressed biomethane generated from grass used as a transport fuel."

Department of Agriculture and Food (DAFF) Research Stimulus: "GreenGrass."

Acknowledgements

Beatrice Smyth and Thanasit Thamsiriroj for advice, brainstorming sessions, conversations and critiques.

References

[1] IEA. Biofuels for transport—an international perspective. International Energy Agency; 2003.
[2] Prasad S, Singh A, Jain N, Joshi HC. Ethanol production from sweet sorghum syrup for utilization as automotive fuel in India. Energy & Fuels 2007;21:2415.
[3] Prasad S, Singh A, Joshi HC. Ethanol as an alternative fuel from agricultural, industrial and urban residues. Resources, Conservation and Recycling 2007;50(1).
[4] EC. Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport. Official Journal of the European Union 2003;L123:42–6.
[5] EC. Directive 2009/28/EC of The European Parliament and of The Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union 2009:16.
[6] Murphy JD, Power NM. An argument for using biomethane generated from grass as a biofuel in Ireland. Biomass and Bioenergy 2009;33:504.
[7] Gerin PA, Vliegen F, Jossart J-M. Energy and CO_2 balance of maize and grass as energy crops for anaerobic digestion. Bioresource Technology 2008;99:2620.
[8] Korres NE, Singh A, Nizami AS, Murphy JD. Is grass biomethane a sustainable transport biofuel? Biofuels, Bioproducts and Biorefining 2010;4:310–25.
[9] Nizami A-S, Murphy JD. What type of digester configurations should be employed to produce biomethane from grass silage? Renewable and Sustainable Energy Reviews 2010;14:1558.
[10] Ward AJ, Hobbs PJ, Holliman PJ, Jones DL. Optimisation of the anaerobic digestion of agricultural resources. Bioresource Technology 2008;99: 7928.
[11] Nizami A-S, Korres NE, Murphy JD. Review of the integrated process for the production of grass biomethane. Environmental Science & Technology 2009;43:8496.
[12] Weiland P. Biomass design in agriculture: a successful pathway for the energy production and waste treatment in Germany. Engineering in Life Sciences 2006;6:302.
[13] Cherubini F, Bird ND, Cowie A, Jungmeier G, Schlamadinger B, Woess-Gallasch S. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. Resources, Conservation and Recycling 2009;53:434.
[14] Singh A, Pant D, Korres NE, Nizami AS, Prasad S, Murphy JD. Key issues in life cycle assessment of ethanol production from lignocellulosic biomass: challenges and perspectives. Bioresource Technology 2010;101:5003–12.
[15] Wenzel MHW, Petersen BM. Life Cycle Assessment of Slurry Management Technologies, Environmental Project No. 1298-2009. Danish Ministry of the Environment: Environmental Protection Agency; 2009.
[16] Coulter B, Lalor S. Major & micronutrient advice for productive agricultural crops. Teagasc 2008.
[17] Singh A, Smyth BM, Murphy JD. A biofuel strategy for Ireland with an emphasis on production of biomethane and minimization of land-take. Renewable and Sustainable Energy Reviews 2010;14:277.
[18] Smyth BM, Murphy JD, O'Brien CM. What is the energy balance of grass biomethane in Ireland and other temperate northern European climates? Renewable and Sustainable Energy Reviews 2009;13:2349.
[19] Karagiannidis A, Perkoulidis G. A multi-criteria ranking of different technologies for the anaerobic digestion for energy recovery of the organic fraction of municipal solid wastes. Bioresource Technology 2009;100:2355.
[20] DeBaere L. Anaerobic digestion of municipal solid waste: residual waste. Belgium: Organic Waste Systems; 2006.
[21] DeBaere L. Dry continuous anaerobic digestion of energy crops. Belgium: Organic Waste Systems; 2007.
[22] DeBaere L. The Dranco process: a dry continuous digestion system for solid organic waste and energy crops. In: International symposium on anaerobic dry fermentation. 2008. p. 108.
[23] Parawira W. Anaerobic treatment of agricultural residues and wastewater. Application of high-rate reactors. Department of Biotechnology, vol. PhD. Sweden: Lund University; 2004.
[24] Lettinga G. Anaerobic digestion and wastewater treatment systems. Antonie van Leeuwenhoek 1995;67:3.
[25] Lehtomäki A, Huttunen S, Lehtinen TM, Rintala JA. Anaerobic digestion of grass silage in batch leach bed processes for methane production. Bioresource Technology 2008;99:3267.
[26] Hulshoff Pol LW, de Castro Lopes SI, Lettinga G, Lens PNL. Anaerobic sludge granulation. Water Research 2004;38:1376.
[27] Cirne DG, Lehtomäki A, Björnsson L, Blackall LL. Hydrolysis and microbial community analyses in two-stage anaerobic digestion of energy crops. Journal of Applied Microbiology 2007;103:516.
[28] Lehtomäki A, Björnsson L. Two-stage anaerobic digestion of energy crops: methane production, nitrogen mineralisation and heavy metal mobilisation. Environmental Technology 2006;27:209.
[29] EC. Well-to-wheels analysis of future automotive fuels and power trains in the European context. European Council for Automotive R&D; 2006.
[30] Power NM, Murphy JD. Which is the preferable transport fuel on a greenhouse gas basis; biomethane or ethanol? Biomass and Bioenergy 2009;33:1403.
[31] ATC, EPHC. Vehicle fuel efficiency potential measures to encourage the uptake of more fuel efficient, low carbon emission vehicles. Public Discussion Paper. Commonwealth of Australia: Australian Transport Council (ATC) and Environment Protection and Heritage Council (EPHC); 2008.
[32] SEI. Energy and CO_2 efficiency in transport: analysis of new car registrations in year 2000. Sustainable Energy Ireland 2003.
[33] Berglund M, Börjesson P. Assessment of energy performance in the life-cycle of biogas production. Biomass and Bioenergy 2006;30:254.
[34] SEI. Emission factors; 2009. http://www.sei.ie/Publications/Statistics_Publications/Emission_Factors/Sustainable Energy Ireland.
[35] Murphy JD, McKeogh E, Kiely G. Technical/economic/environmental analysis of biogas utilisation. Applied Energy 2004;77:407.
[36] EC. Anaerobic digestion of municipal wastes at the city of Kaiserslautern. European Commission; 1993.
[37] Salter A, Banks CJ. Establishing an energy balance for crop-based digestion. Water Science and Technology 2009;59:1053.
[38] Cropgen. Energy balance optimisation for an integrated arable/livestock farm unit. Renewable energy from crops and agrowastes. University of Vienna; 2007.
[39] Persson M. Evaluation of upgrading techniques for biogas. Report SGC 142: Swedish Gas Centre; 2003.
[40] Börjesson P, Berglund M. Environmental systems analysis of biogas systems—Part I: Fuel-cycle emissions. Biomass and Bioenergy 2006;30: 469.
[41] Murphy JD, McKeogh E. Technical, economic and environmental analysis of energy production from municipal solid waste. Renewable Energy 2004;29:1043.
[42] Siuru B. Design promises diesel efficiency from natural gas engines—Technology. Diesel Progress North American Edition, vol. December: http://findarticles.com/p/articles/mi_m0FZX/is_12_68/ai_95954287/?tag=content;col1; 2002.
[43] Kiely G, Leahy P, Sottocornola M, Laine A, Mishurov M, Aldertson J, et al. Celticflux: measurement and modelling of greenhouse gas fluxes from grasslands and peatland in Ireland. EPA Strive Programme 2007–2013. 2001-CD-C2-M1. Ireland: Environmental Protection Agency; 2008.
[44] Whipps JM. Carbon economy. In: Lynch JM, editor. The rhizosphere. Chichester: Wiley; 1990. p. 59.
[45] Saggar S, Hedley C, Mackay AD. Partitioning and translocation of photosynthetically fixed 14C in grazed hill pastures. Biology and Fertility of Soils 1997;25:152.
[46] Freibauer A, Rounsevell MDA, Smith P, Verhagen J. Carbon sequestration in the agricultural soils of Europe. Geoderma 2004;122:1.
[47] Jones MB, Donnelly A. Carbon sequestration in temperate grassland ecosystems and the influence of management, climate and elevated CO_2. New Phytologist 2004;164:423.